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INVESTIGATION OF THE PHYSICAL ORIGIN OF MULTIWAVELENGTH VARIABILITY IN ACCRETING COMPACT OBJECTS

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Abstract: This paper deals with the effects of physical processes on multiwavelength variability of intermediate polars. Intermediate polars are binary systems consisting of a white dwarf that accretes matter from a red dwarf. This causes variability in the system's observed brightness and spectra, making intermediate polars variable stars. The process of inverse Compton scattering was simulated for changing parametres of the system. For the simulation, Monte Carlo methods were used. We found that in the hot post-shock region, photon energies are increased by inverse Compton scattering. The effects vary with changing mass accretion rate, where for higher mass accretion rate, photons are upscattered to higher energies.

1 Introduction

Variable stars are objects that have been observed to undergo changes in apparent brightness, either caused by physical factors or the geometry of observations. Intermediate polars are cataclysmic variable stars, semi–contact binary systems consisting of a white dwarf primary star and a lighter red dwarf secondary star. Matter accretes onto the heavier primary. Its magnetic field is strong enough to stop the formation of classical accretion disk, instead making it truncated in the inner part. Inside of the magnetosphere, the matter is frozen onto induction lines and is forced to follow them onto the white dwarf surface in an accretion column. The infalling matter creates shock when its velocity exceeds the local sound speed and the post–shock region is heated. Most of emission from this region comes from cooling processes (cooling flow): bremsstrahlung radiation, cyclotron radiation and Compton cooling, the former two processes being dominant. Inverse Compton scattering can give scattered photons significantly larger energies than they originally had. This paper focuses on the effects of inverse Compton scattering and its contribution to the overall changes in spectrum of intermediate polars. Monte Carlo simulations were applied to this problem. We also studied the effects of changing a physical parameter of the system, the mass accretion rate, on the process of inverse Compton scattering.

2 Theoretical background

Intermediate polars are binary systems falling under the category of cataclysmic variable stars (Percy, 2005). The primary component of these binaries is a white dwarf, the secondary component is a red dwarf, a cool star on the main sequence. The gravitational potential around two massive objects isn't spherically symmetrical. It deforms to form Roche lobes. In cataclysmic variables, components of the binary system are so close together that the red dwarf fills its Roche lobe and loses matter through the inner Lagrangian point. This mass is transferred onto the white dwarf. If there is no strong magnetic field present, this matter will first form an accretion disk which would lead the matter all the way to the white dwarf surface.

In polars and intermediate polars, the magnetic field of the white dwarf is so strong that the accretion disk is truncated in the middle (intermediate polars) or can't form at all (polars) and the matter follows the magnetic field lines onto the poles of the white dwarf where it falls in an accretion column (Hellier, 2001). This matter is heated to high temperatures by falling into a gravitational well. The free-fall velocity exceeds the speed of sound in the medium and a shock front is created.

The conditions in this region are so hot that the photons emitted from the white dwarf's surface can gain energy by scattering off relativistic electrons. This is one of the cooling mechanisms of the accretion column. Bremsstrahlung and synchrotron radiation are other important cooling processes in this region (Rybicky & Lightman, 2004).

Bremsstrahlung emission (or free–free emission) is the radiation created due to the deceleration of a charge in the Coulomb field of another charge. It can be easily described in a classical way with the quantum results only appearing as corrections contained in the Gaunt factor.

If a charged particle moves in a magnetic field, it will experience a force acting on it, and therefore it will accelerate. Such particle will then emit radiation – cyclotron radiation if the particle is moving with non–relativistic velocity or synchrotron radiation for relativistic velocities, where the frequency spectrum is much more complex (Rybicky & Lightman, 2004).

Thomson scattering happens when photons with low energies scatter from free charges. If the moving electron has a large enough kinetic energy compared to the photon, energy can be transferred from the electron to the photon. This effect is called the inverse Compton scattering. Some conditions will significantly alter the scattered photons' energies. For sufficiently dense media, multiple Compton scattering events can occur before the photon escapes.

3 Data analysis

We used Monte Carlo simulation methods to simulate this environment. The Monte Carlo simulations are quasi-random. Each particle interaction will produce a different result, but by repeating the simulation many times (in our case, 10 000 model interactions), the end distribution will not be random anymore. In our code we first focused on one-on-one photon and electron interaction which we then repeated using various parametres.

First we had to test our code. We plotted the Klein-Nishina cross section from the spectral distributions that we simulated (Fig. 1). For low electron energies we get the Tomson cross section shaped like a peanut, which hints that our photons will scatter into all directions. With rising electron energies the photons focus their directions into a narrow range of angles.

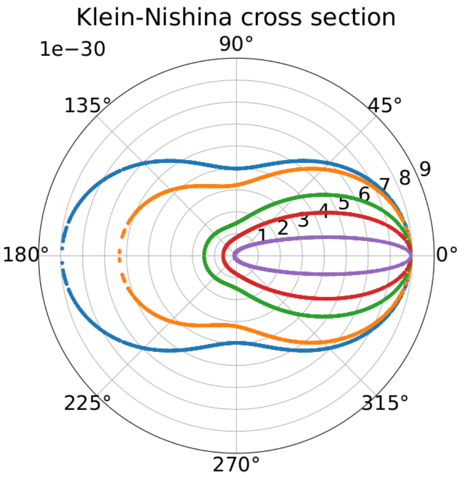

Figure 1: Klein-Nishina cross section for various photon energies in units [m^{-2}]. The radial coordinate in the plot $r \in \langle 0, 9 \times 10^{-30} \rangle$. The blue, orange, green, red and purple distributions correspond to 2.75 zeV, 60 keV, 511 keV, 1.46 MeV and 10 MeV, respectively.

We simulated both, optically thin (each photon scatters exactly once) and opticaly thick environment (each photon may scatter multiple times before leaving the medium). For repeating interactions we modeled a virtual photon. A “part” of it would scatter and a “part” would stay in the medium and continue scattering until the weight of the interaction got low enough, at which point we assumed the photon has escaped the medium.

The most important parameters of the simulations were the blackbody temperature (the WD temperature) for scattering of a spectrum, and the spectral line frequency for scattering of a spectral line, which described the photons interacting, and the electron temperature. We used a 1D model, assuming spherically symmetrical medium. Since the height of the accretion column changes significantly with changing mass accretion rate, for the spatial parameter we used, we chose the diameter of the accretion column, which doesn’t change as much.

Our model was 1-dimensional, which is quite a simplification. In the real accretion column, the temperature, density and pressure change with height above the white dwarf surface, and the accretion column has two important spatial dimensions, width and height. To apply this into our code, we’d have to include the computation of the changing parameters through the environment, directly into the scattering process itself. With every single scattering, these parameters would be different. We would also have to assume that every photon traveled a different distance through the medium, depending on whether it moved diagonally through it, up or to the side.

To compute the photon scattering in an optically thick environment, we must define the photon mean free path, which is the distance that photon can travel in the medium without interacting with an electron. This quantity is of the same order of magnitude as the accretion column width. Our simulation would only allow the photon to escape the medium after it had crossed that distance. This means the model photons could scatter once or multiple times.

4 Results

We first applied our code to parameters already studied by other authors (Pozdnyakov & Sobol & Syunyaev, 1983) and (Pozdnyakov & Sobol & Syunyaev, 1977). We firstly studied optically thin environment. We confirmed that for increasing electron temperatures the photons will upscatter towards higher energies, just as the theory predicted (Figs. 2, 3 and 4).

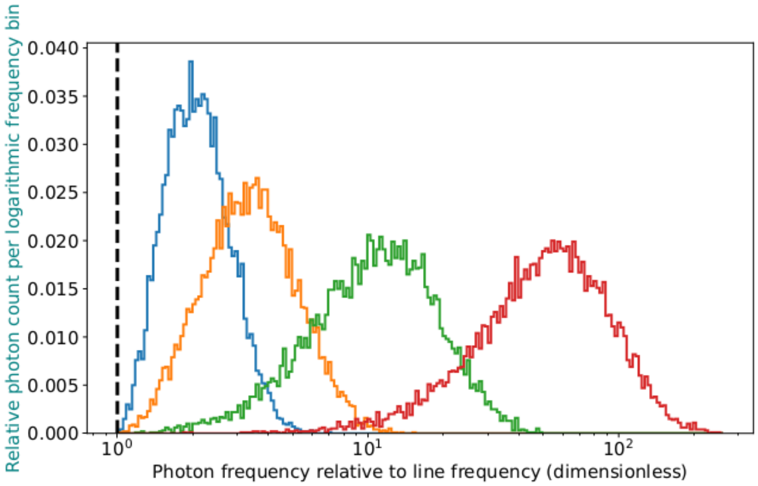

Figure 2: Frequency distribution of the 6.4 keV emission line photons scattered off electrons of four different energies. The blue, orange, green and red distributions correspond to 0.1 MeV, 0.25 MeV, 1 MeV and 5 MeV, respectively. The original line is marked in black.

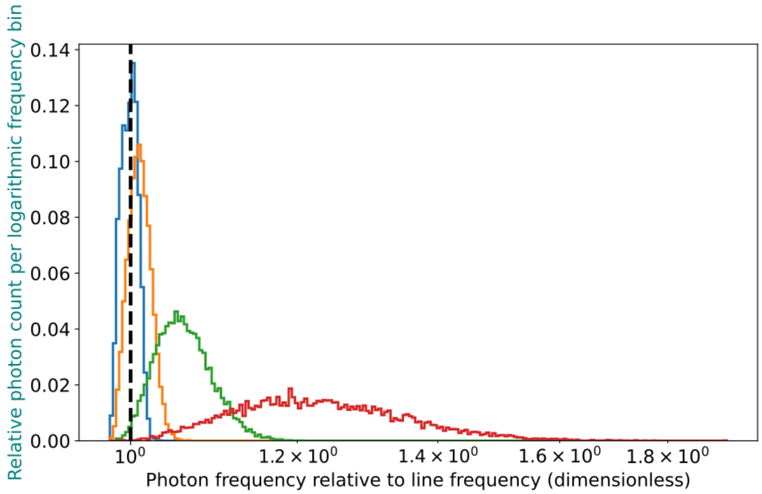

Figure 3: Frequency distribution of the 6.4 keV emission line photons scattered off electrons of four different energies. The blue, orange, green and red distributions correspond to 25 eV, 100 eV, 1 keV and 10 keV, respectively. The original line is marked in black.

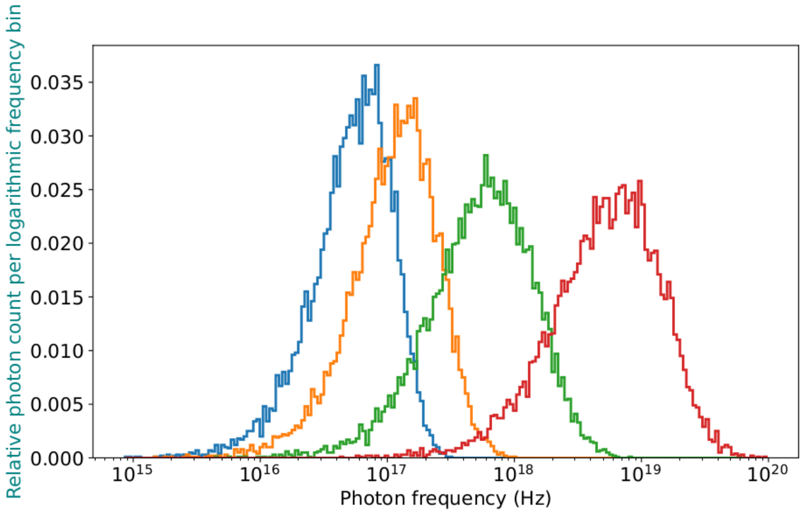

Figure 4: Frequency distribution of 100 eV (roughly 1.16×10^6 K) blackbody spectrum photons scattered off electrons of three different energies. The blue, orange, green and red distributions correspond to the original spectrum, scattered spectrum off 100 keV electrons, 1 MeV electrons and 10 MeV electrons, respectively.

For optically thick environment we see how multiple scatterings changed blackbody radiation or a spectral line (Figs. 5 and 6). The more a photon scatters, the more it's upscattered into shorter wavelengths.

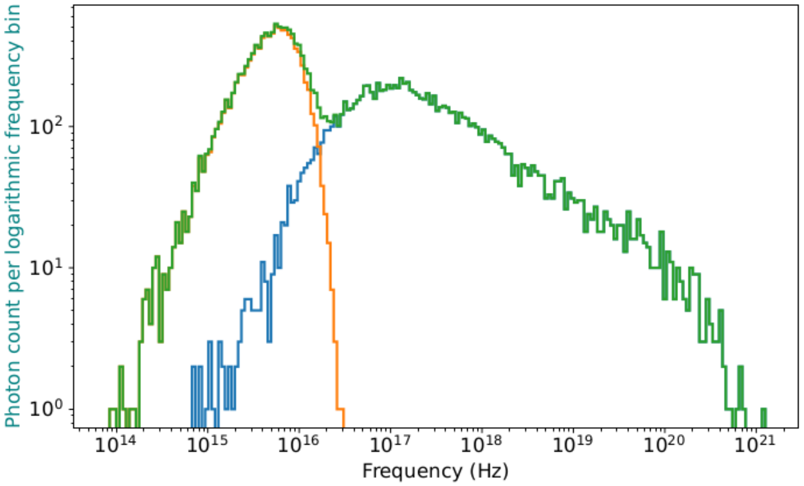

Figure 5: Distributions of incident (orange) and scattered (blue) photons resulting from the inverse Compton scattering of a black body (temperature 10^5 K) spectrum scattering off electrons at the shock front. The resulting spectrum, a combination of both incident and scattered, is depicted in green.

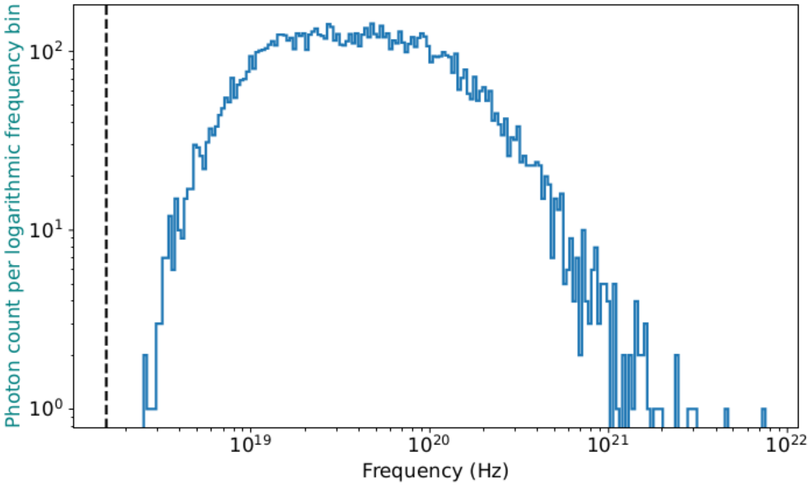

Figure 6: Distribution of photons resulting from inverse Compton scattering of the 6.4 keV line off electrons at the shock front. The original line is marked in black.

In our simulation we focused on the changes in mass accretion rate and how they influence the emergent spectra. Changing the mass accretion rate will lead to changes in the accretion column (see Fig. 7).

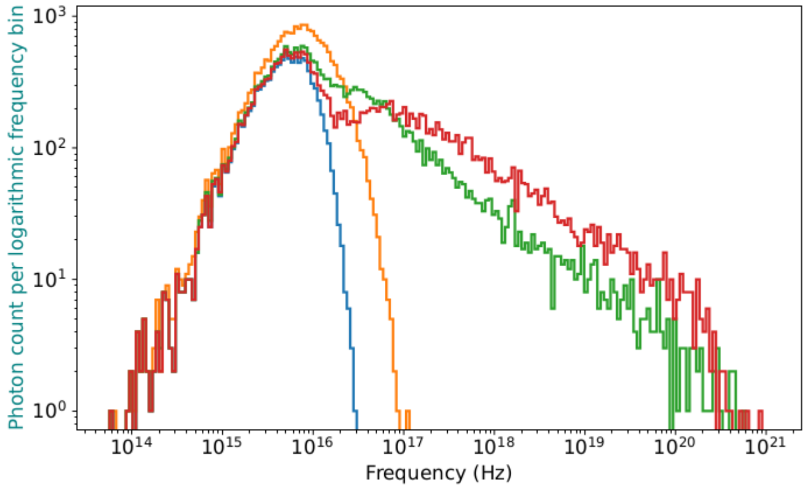

Figure 7: Distributions of incident (blue) and scattered photons resulting from the inverse Compton scattering of a black body (temperature 10^5 K) spectrum scattering off electrons at the shock front. Orange, green, and red scattered spectrum corresponds to $\dot{M}$: $\dot{M}_1 = 5 \times 10^{13}$ kg s^{-1}, $\dot{M}_2 = 10^{14}$ kg s^{-1} and $\dot{M}_3 = 2 \times 10^{14}$ kg s^{-1}, respectively.

It thus represents a source of variability in these systems. We can safely assume that these changes will also influence the observations. Mass transfer rate is therefore an important parameter to consider when modeling the spectra of intermediate polars. We have shown that for a low mass accretion rate, the emergent spectrum will not be much different than the original black-body spectrum. However, with a growing mass accretion rate, the dimensions of the accretion column change and the electron temperature grows. The photons will be upscattered to even higher energies and shorter wavelengths.

We could apply our findings to estimate the white dwarf mass from gathered spectra. Accretion column temperature is influenced by the white dwarf mass and therefore it can be found through this relation. With a growing temperature, the escaping photons will get more energetic which may represent a reliable indicator in observations. With a growing magnetic field, however, the cooling processes change their dominance which must be considered in the calculations.

5 Conclusions or Summary

To conclude, our findings were the same as other author's (Pozdnyakov & Sobol & Syunyaev, 1983) and (Pozdnyakov & Sobol & Syunyaev, 1977). The simulated inverse Compton scattering process changes the emergent spectra of the system. For electron temperatures corresponding to the temperatures found in accretion column the photons will be upscattered to higher energies. This process, however, isn't dominant in the accretion column. The theoretical models and other authors' work confirm that the inverse Compton scattering process is much less dominant than bremsstrahlung radiation or synchrotron radiation. This suggests that more research can be done in this field to include these other processes in our calculations and then compare those results with observed spectra.

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